Study of multi-muon events at CDF

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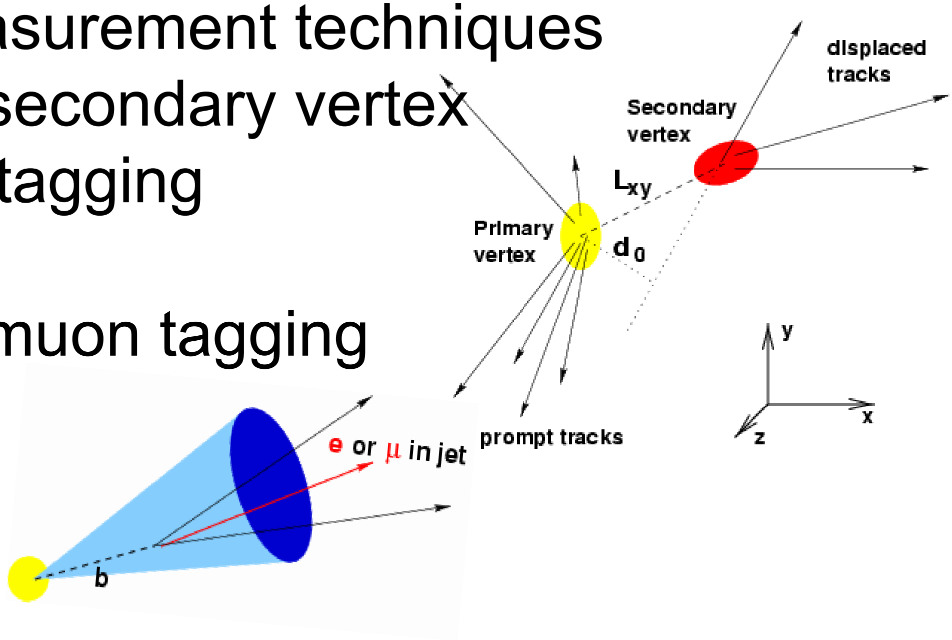
Outlook

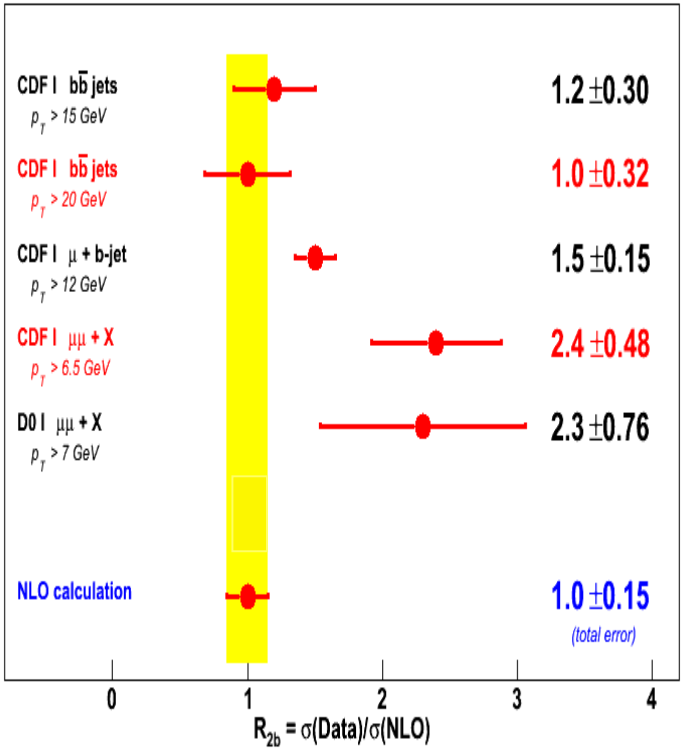
- Physics motivation:
  - puzzles in *b* production and decays from the past
    - Correlated *bb* production, σ_{bb}
    - Invariant mass spectrum of dileptons from b sequential decays
    - $\bar{\chi}$: time integrated mixing probability
- Recent results:
  - new and very precise measurement of σ_{bb} agrees with the prediction [PRD 77,072004 (2008)]
- Study of the multi-muon events responsible for the previous discrepancies arXiv:0810.5357[hep-ex]

Correlated $b\bar{b}$ cross section

Two central *b*'s with p_T>6 GeV/c² .Small theoretical uncertainty (15%), LO diagrams dominate

- Measurement techniques
  - secondary vertex tagging
  - muon tagging





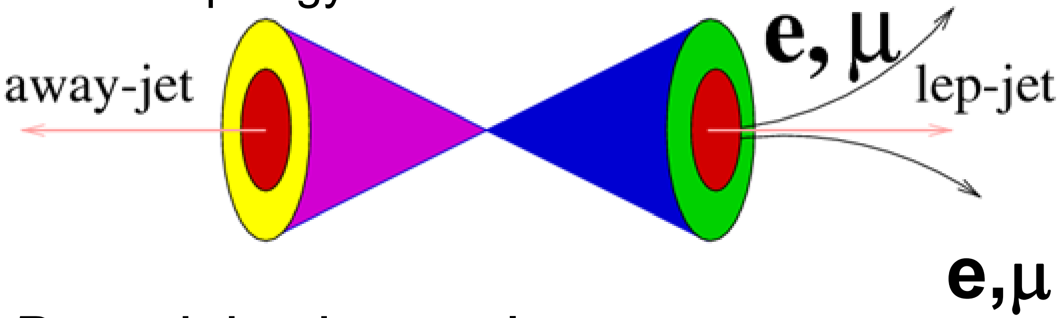
•R_{2b} = σ_{bb}(measured)/σ_{bb}(NLO)
- Vertex tag analyses → R_{2b} =1
- **Analyses using muon tags → R_{2b} > 1**

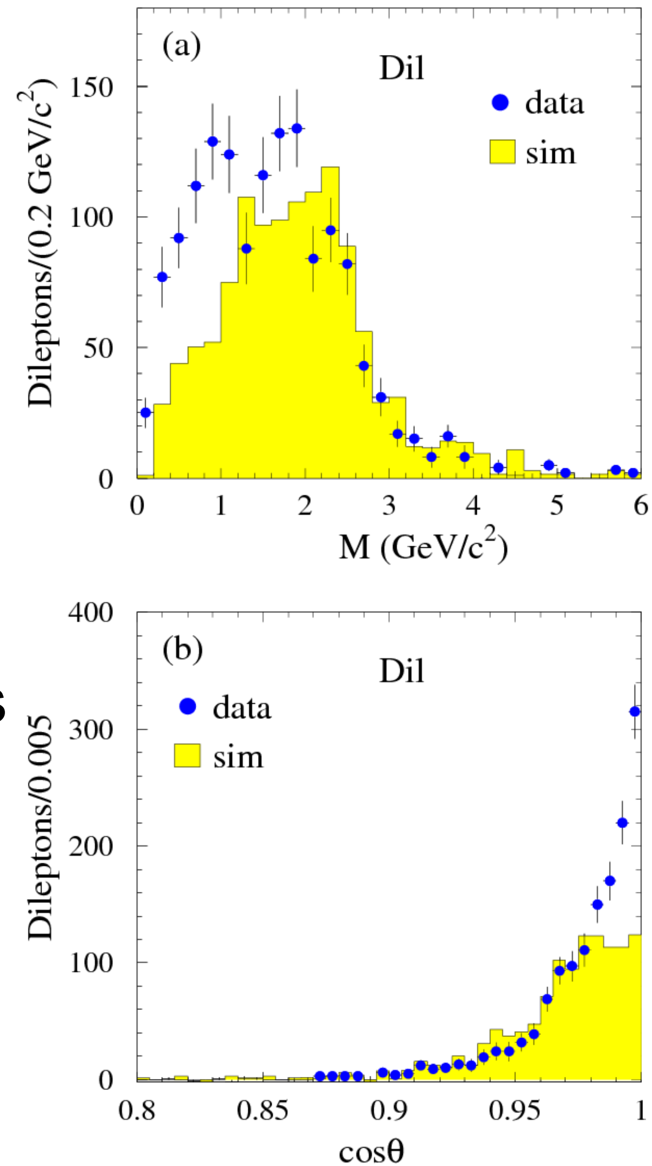
$$\sigma\left(p\bar{p} \rightarrow b\bar{b} \rightarrow llX\right)$$

larger than NLO ∝ N(μ)

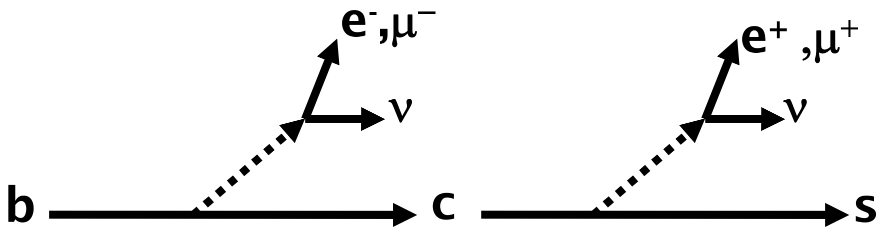
low mass dileptons

Event topology





- *B* enriched sample:
  the low mass di-lepton invariant mass is not well modeled by sequential semi-leptonic decays of single *b* quarks



- Simulation: HERWIG+EVTGEN

PRD 72, 072002 (2005)

$\bar{\chi}$

The average $B^0\bar{B}^0$ mixing probability is defined as:

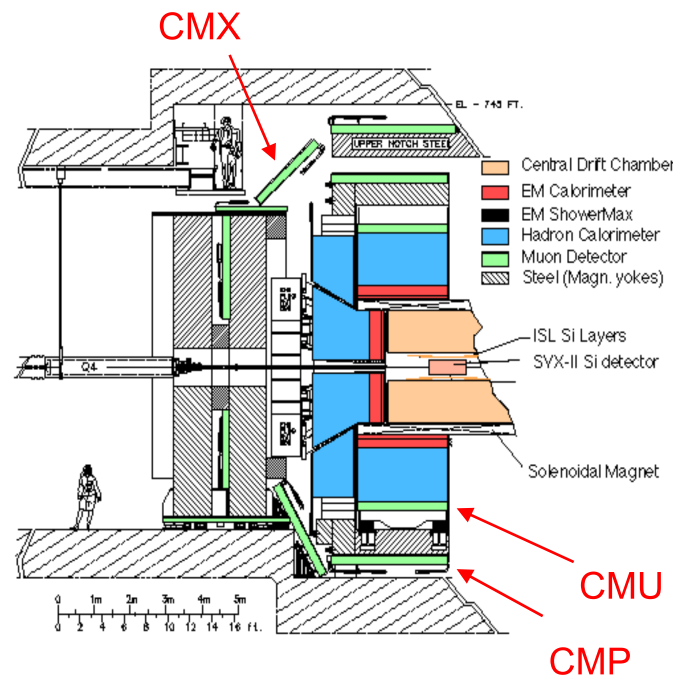
$$\bar{\chi} = \frac{\Gamma(B^0 \to \bar{B}^0 \to l^+ X)}{\Gamma(B \to l^\pm X)} = \frac{"same\ sign"}{"total"},\ B^0 = B_d^0\ or\ B_s^0$$

In absence of mixing, the double semileptonic decay of a $B^0\bar{B}^0$ pair results in an OS lepton pair; when one of the hadrons undergoes mixing a SS lepton pair is produced. CDF run I result is higher than the combined LEP one:

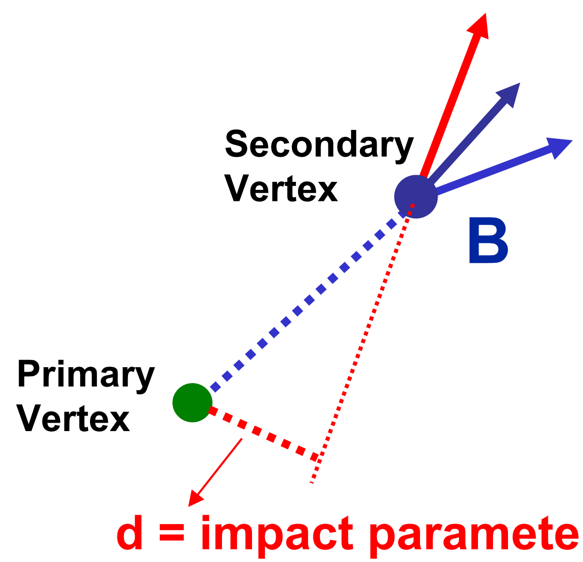
0.152±0.013 vs 0.126±0.004

New measurement of $\sigma\left(p\bar{p} \to b\bar{b} \to \mu\mu X\right)$

- Data sample used in this analysis (~750pb^{-1}) defined by a trigger requiring 2 muons with:
  - Central track with p_T > 3 GeV, $|\eta|<0.7$
  - Match to stub in CMU and CMP (CMUP)
  - $5<M_{\mu\mu}<80$ GeV (no Z's, J/ψ , $b \to c\mu \to \mu\mu X$)

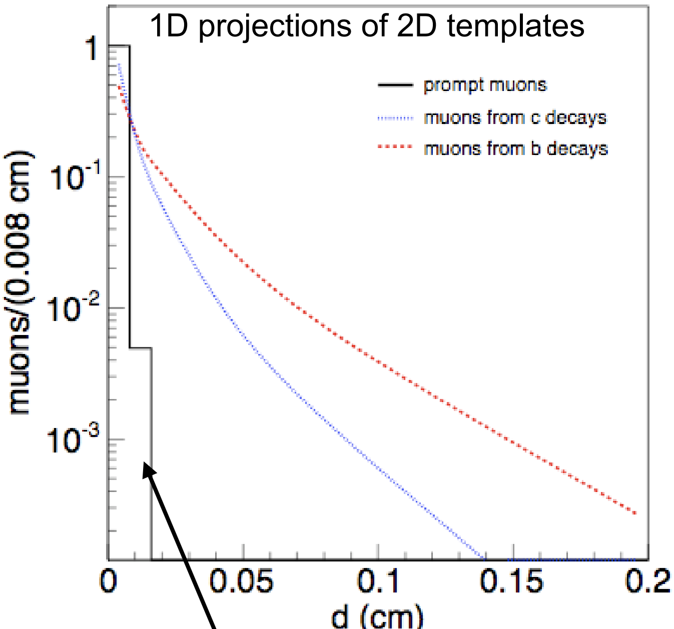


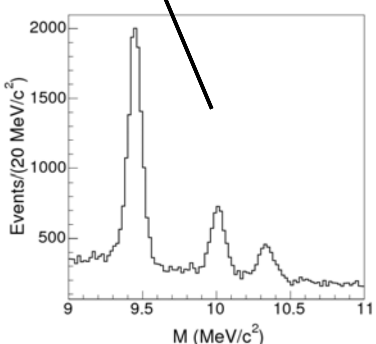
- Known sources of real muons are:
  - $b \to \mu$ ($c\tau$ = 470 μm), $c \to \mu$ ($c\tau$ = 210 μm)
  - Prompt muons (Y, Drell-Yan)
- Known sources of fake muons include:
  - Hadrons punching through calorimeter
  - Decays in flight ($K_s \to \mu$, $\pi \to \mu$)
  - Fake muons can be from prompt or h.f. decays



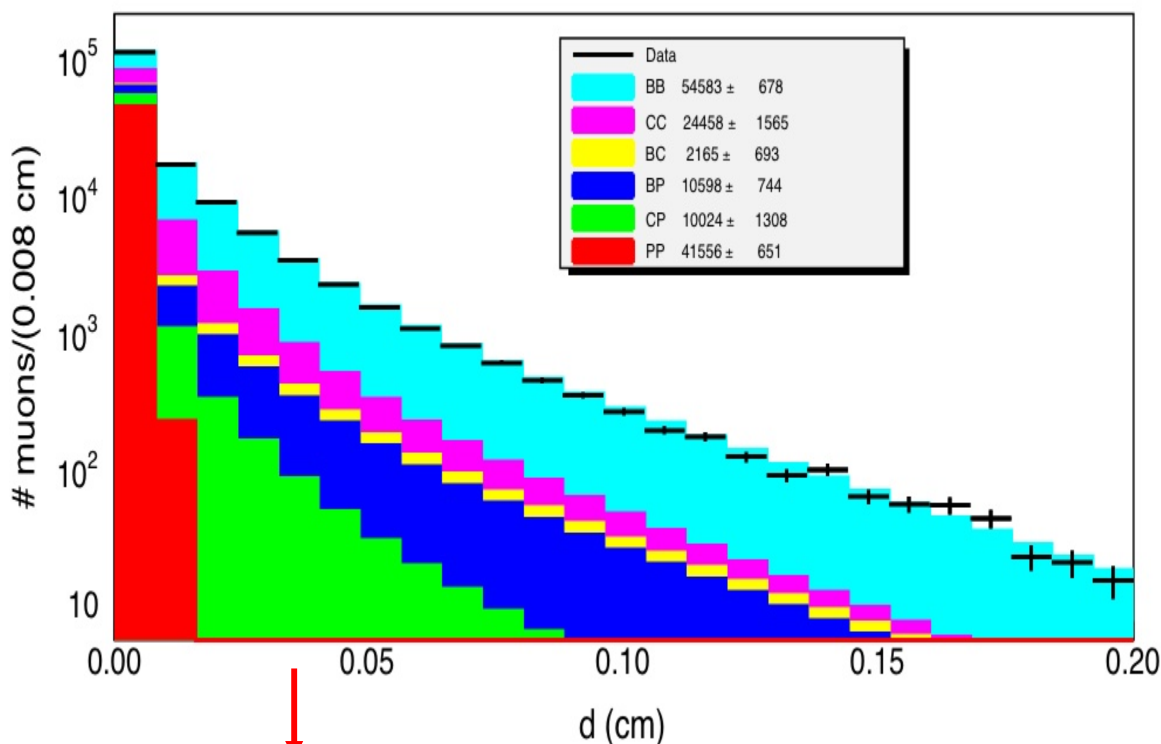
New measurement of σ_{bb} : experimental method

- Extract the sample composition by fitting the observed d distribution of the muons [2D fit - $d_0(\mu_1)$ vs $d_0(\mu_2)$] with the expected d distributions of muons from various sources and for all the combination (*bb*,*cc*,pp,*bc*,*b*p,*c*p)
- Derive templates for h.f (MC) and Prompt (Y from data)



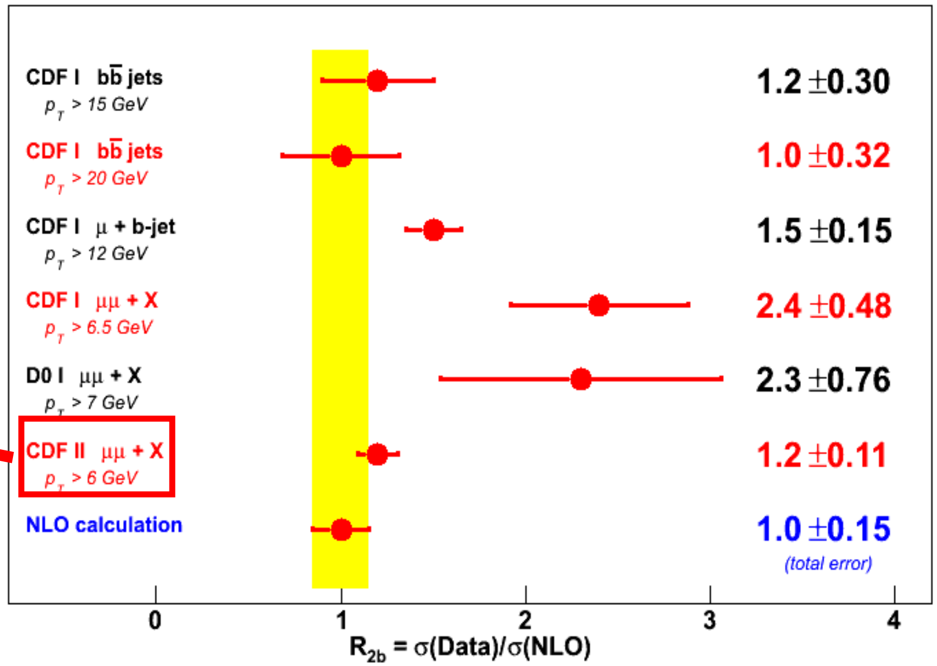


Y



The sum of these contributions is "improperly" referred to as QCD

New measurement of σ_{bb} : results



- Very accurate
- Appreciably smaller than Run I results

$\sigma_{b\bar{b}} = 1328 \pm 209 nb$ NLO

$\sigma_{b\bar{b}} = 1618 \pm 148 nb$ Data

$(p_T > 6 GeV \quad |\eta| < 1.0)$

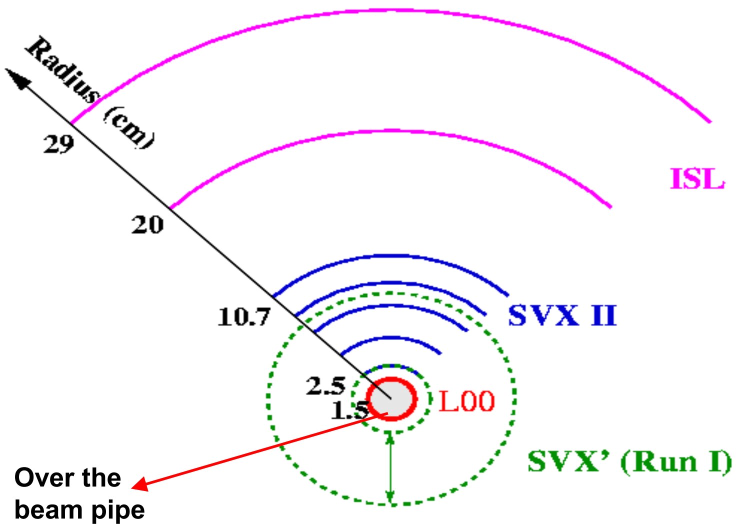
WHY?

Investigating the differences: tracking

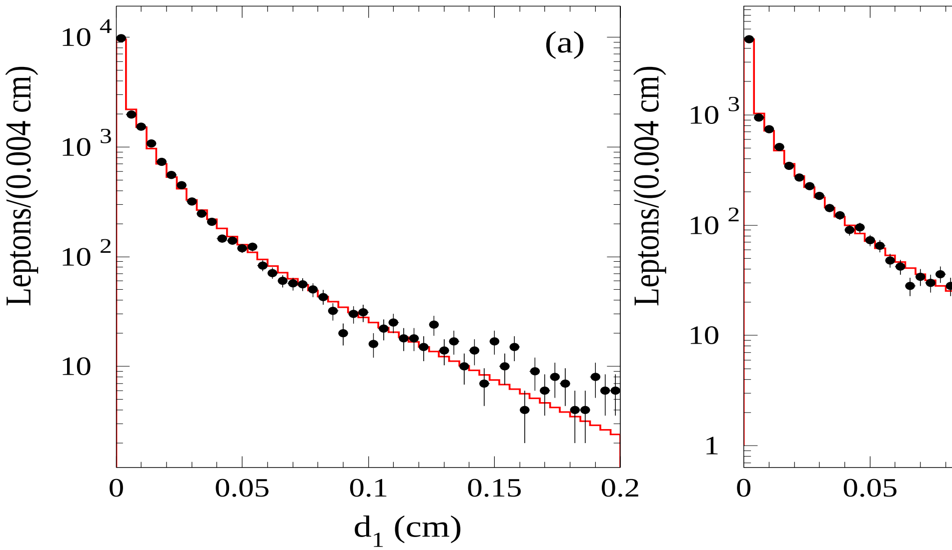
To achieve an impact parameter resolution (σ_d) of ~ 30 μm tracks are reconstructed using at least three hits in the silicon detector (standard SVX selection)

Impact parameter resolution:

- 230 μm (COT only tracks)
- 30 μm (COT + $\geq$ 3 SVX hits)



SVX II (L00, L0, L1, L2, L3, L4)



However, the only way of modeling the data was using tight SVX requirements (hits in L0, L00 and two of the remaining L1-L4 layers.

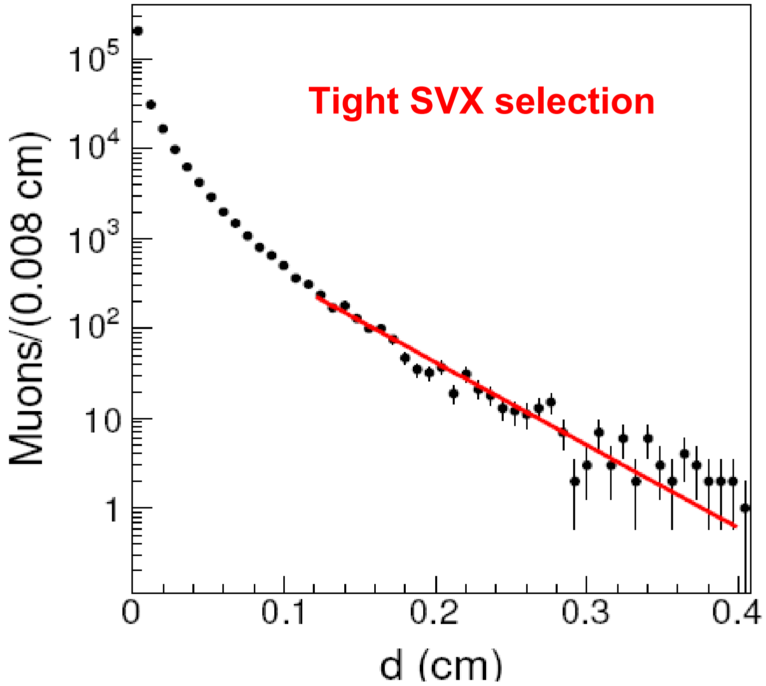
This selection requires that both muons originate inside the beam pipe but does not improve σ_d

Tight SVX efficiency

- evaluate efficiencies using control samples of data
  - Prompt: (25.7±0.4)% using Y and Z
  - Heavy Flavor: (23.7±0.1)% using $B \to J/\psi, B \to J/\psi K, B \to \mu D^0$
- if the dimuon sample before the tight SVX had the composition determined by the fit, the average efficiency of the tight SVX requirement, $\varepsilon_{\text{tight SVX}}$, would be 0.244±0.002 whereas it is measured to be 0.1930±0.0004
- this difference implies that there is a class of events that is rejected by the tight SVX selection more than QCD events
- in the following we assume that this class of events is completely rejected by the tight SVX selection

QCD events

Assume that the tight SVX selection only isolates known sources of dimuon events that we call QCD



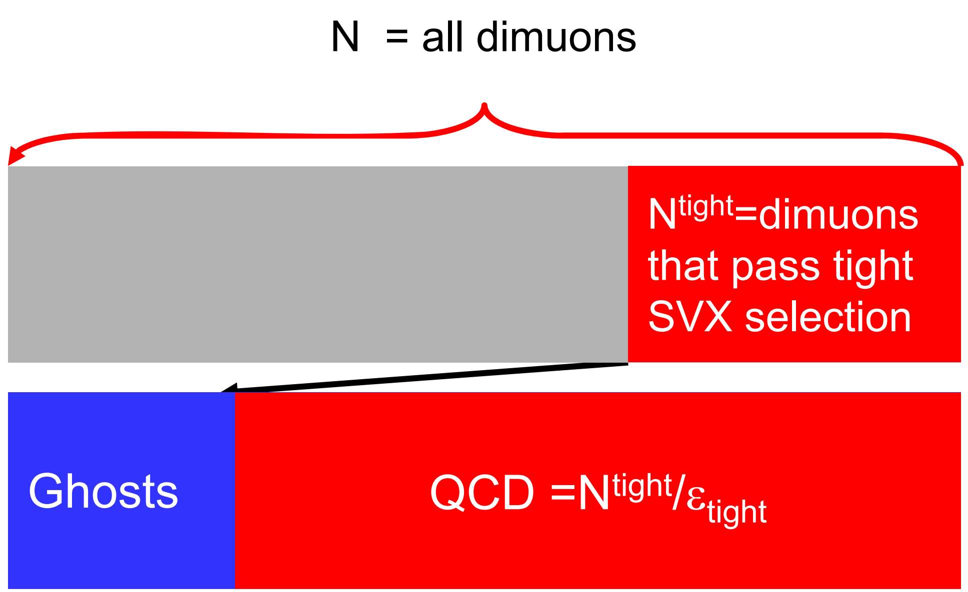
- Charm contribution minimal for $d_0 > 0.12$ cm
- Fit d_0 distribution for muons with $0.12 < d_0 < 0.4$ cm
  - ✓ Measure $c\tau = 469.7 \pm 1.3\ \mu m$ (stat. error only)
  - ✓ PDG average *b* lifetime: $c\tau = 470.1 \pm 2.7\ \mu m$
  - ✓ Reasonable initial assumption

Conclude that:

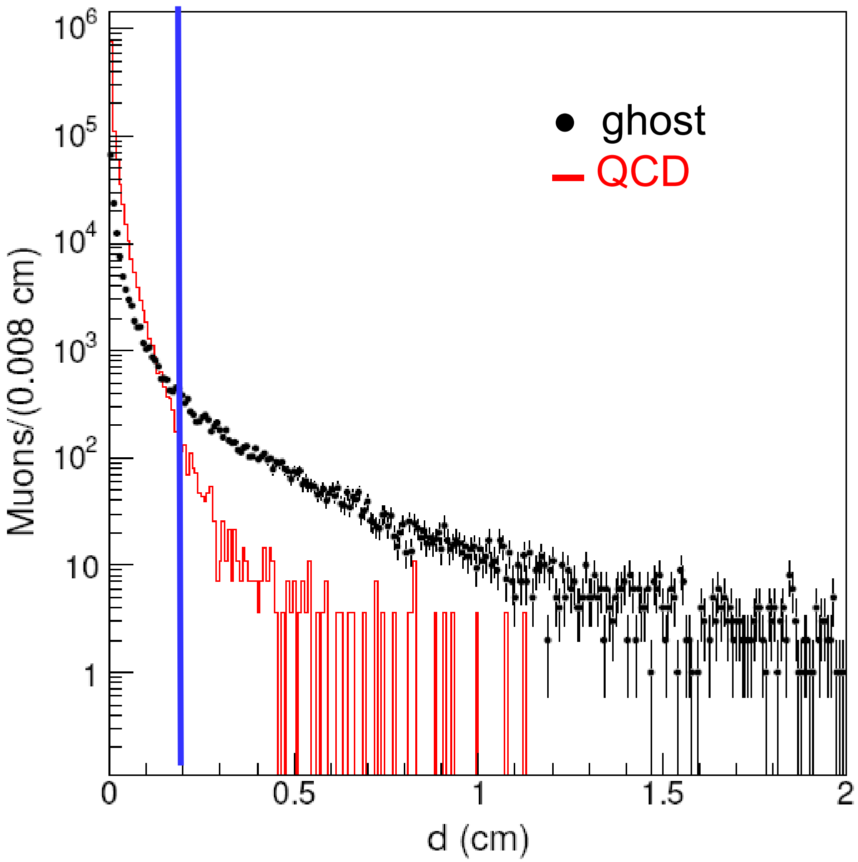
- QCD sample (selected with tight cuts) not significantly affected by additional background
- *b* contribution almost fully exhausted for $d_0 > 0.5$ cm

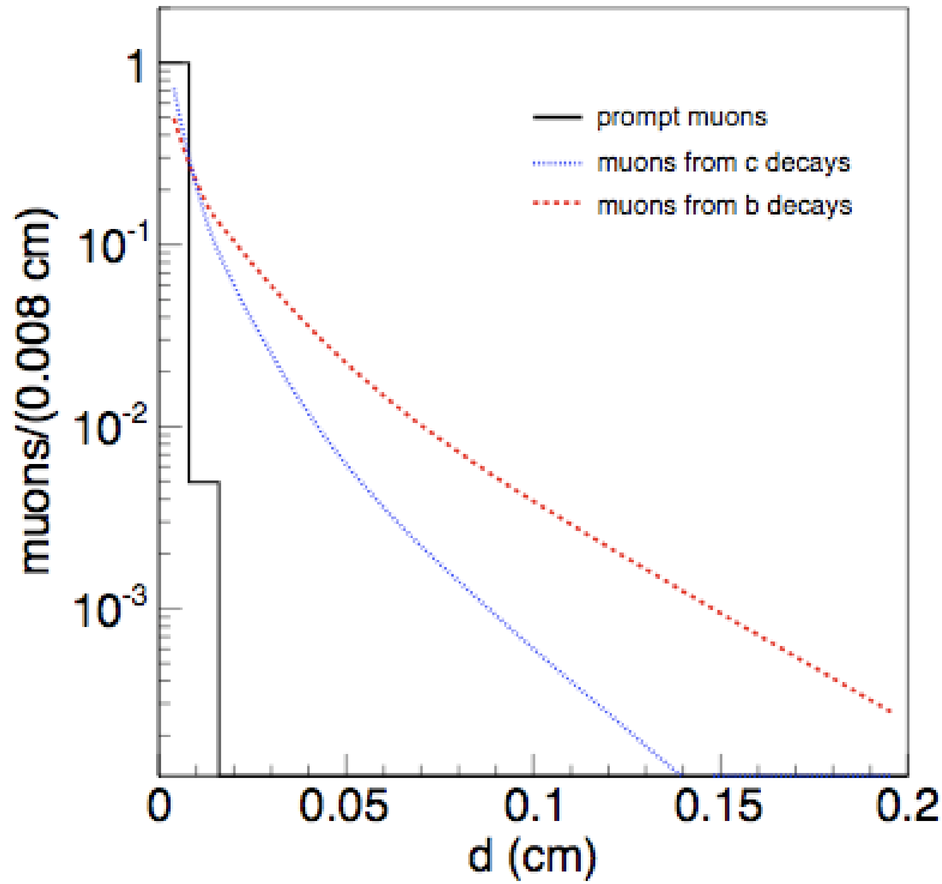
Ghost events

- N is the number of dimuons events prior to any SVX requirement;
- N^{tight} = number of events passing tight SVX req's
  sum of contributions determined by the fit of the $b\bar{b}$ cross section analysis [*b*, *c*, prompts]
- $QCD = N^{tight}/\varepsilon_{tight\ SVX}$
- GHOST = N – QCD



Impact parameter distribution of trigger muons in QCD and Ghost events





- QCD sources of dimuons have d_0<0.5 cm
- Ghost events have a different impact parameters distribution
- below 0.2 cm the fit interprets these events as heavy flavors

Number of QCD and Ghost events

Type	No SVX	Tight SVX	standard SVX
All	743006	143743	590970
All OS		98218	392020
All SS		45525	198950
QCD	589111 ± 4829	143743	518417 ± 7264
QCD OS		98218	354228 ± 4963
QCD SS		45525	164188 ± 2301
Ghost	153895 ± 4829	0	72553 ± 7264
Ghost OS		0	37792 ± 4963
Ghost SS		0	34762 ± 2301

measured

$/\varepsilon_{tight}$

$/\varepsilon_{tight}$ *(0.88)

Assume tight selection is all QCD

In standard SVX sample: ghost = N – QCD *ε(=.88)

plausible resolution of previous inconsistencies

Previous σ_{bb} measurements:

- using the standard SVX selection: ~73K ghost events add to ~195K bb events → R~1.3
- No SVX req's: ~150000 ghost events add to ~200000 bb → R~2

$\bar{\chi}$:

Type	standard SVX
QCD	518417 ± 7264
QCD OS	354228 ± 4963
QCD SS	164188 ± 2301
Ghost	72553 ± 7264
Ghost OS	37792 ± 4963
Ghost SS	34762 ± 2301

Corresponds to a value of ~0.12

the addition of these events yields a value of ~0.15

Possible sources of Ghost events

We have investigated ordinary sources of events that could give rise to real or fake muons missing the inner SVX layer.

- In flight decays of $K^{\pm}, \pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$
  evaluated using herwig Monte Carlo ~57000 evts
- Long-lived hadrons ($\Lambda \rightarrow p\pi^{-}, K_S^0 \rightarrow \pi^{+}\pi^{-}$)
  evaluated using data ~12000 evts
- Secondary interactions of hadrons
  in the detector volume no evidence

We can explain 50% of the total ghost sample (153895 evts)

Search for additional muons

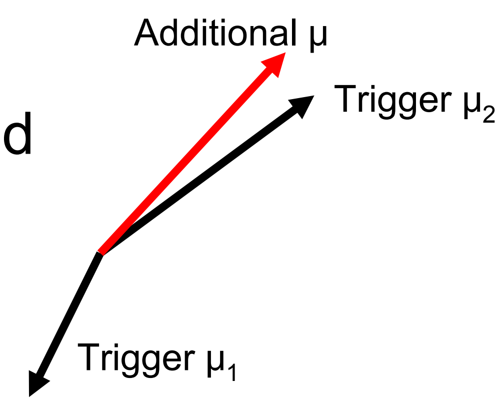
- If the Ghost events are all due to the known sources that we have investigated, the request of additional muons will decrease the contribution of ghost with respect to QCD that contains also b sequential decays

  – 0.9±0.1 % of Y mesons contain an additional μ
  – 1.7±0.6 % of K^0_S mesons contain an additional μ

$\varepsilon_{\text{tight SVX}}$ should rise from 0.193 towards 0.244 whereas it is measured to be 0.166. This implies that ghost events contain more additional muons than QCD events.

- Ghost events may be related to the excess of low mass dileptons

Search for additional muons with p_T>2 GeV/c and $|\eta|$<1.1 around each initial muon; $M_{\mu\mu}$<5GeV/c^2 - Use CMU+CMP+CMX

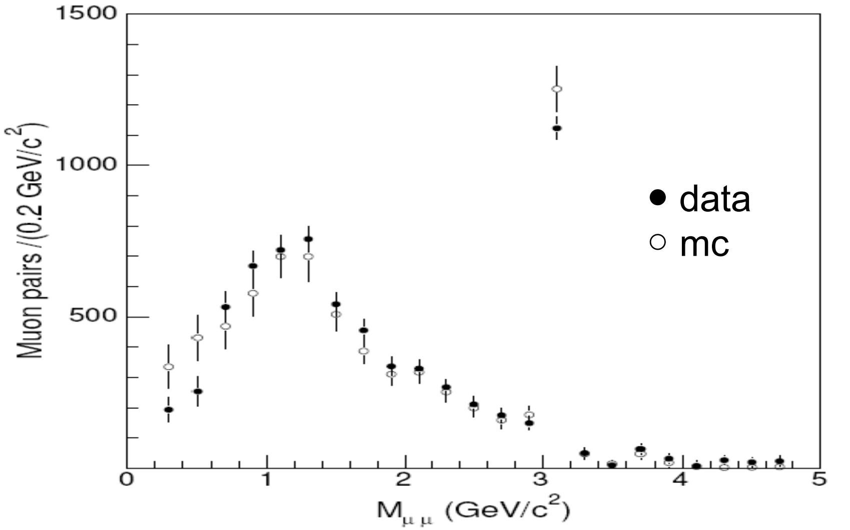


Low mass dimuons-sequential *b* decays

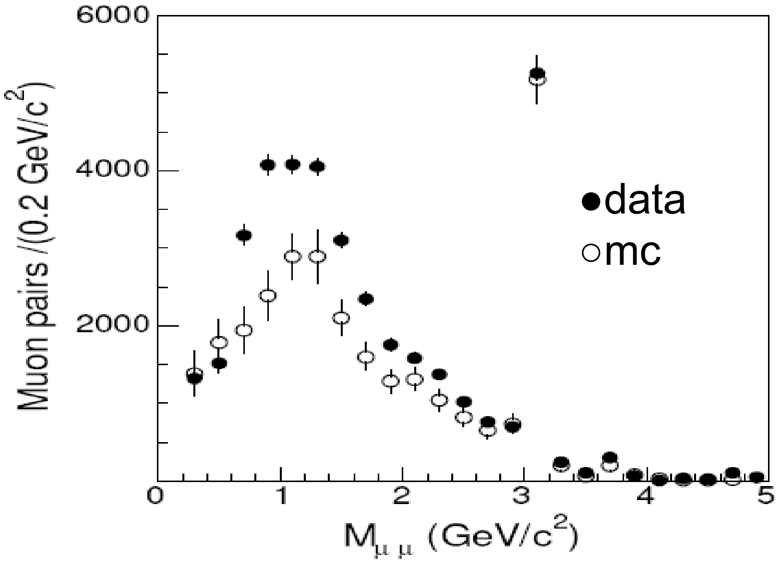
Compare invariant mass in data and simulation that includes fakes

Initial muons pass the tight SVX req's, additional muons no SVX req's

Data: 6935±154
MC: 6998±239

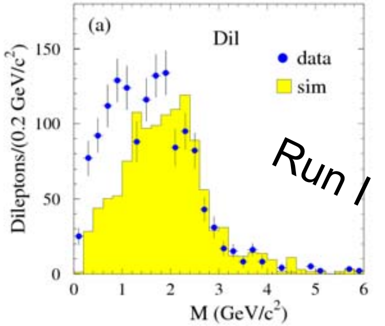


Entire sample no SVX req's :



Excellent agreement on the J/ψ prediction

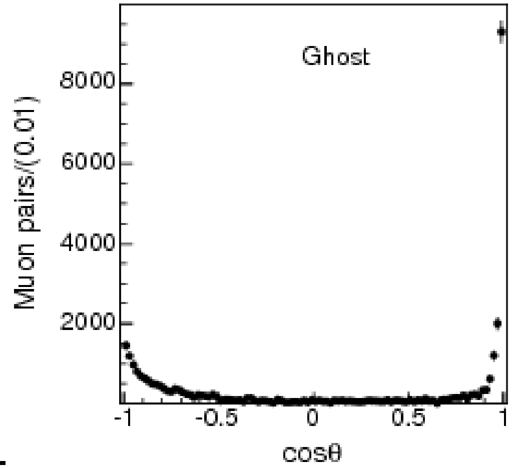
excess at low mass



Run I

Extra muons/tracks in ghosts

In the ghost sample all additional muons are contained in a cosθ>0.8 cone around the trigger muons.



# of additional muons in ghost

Topology	Observed	F_K	F_π
OS	28692 ± 447	15447 ± 210	9649 ± 131
SS	20180 ± 246	10282 ± 137	6427 ± 81

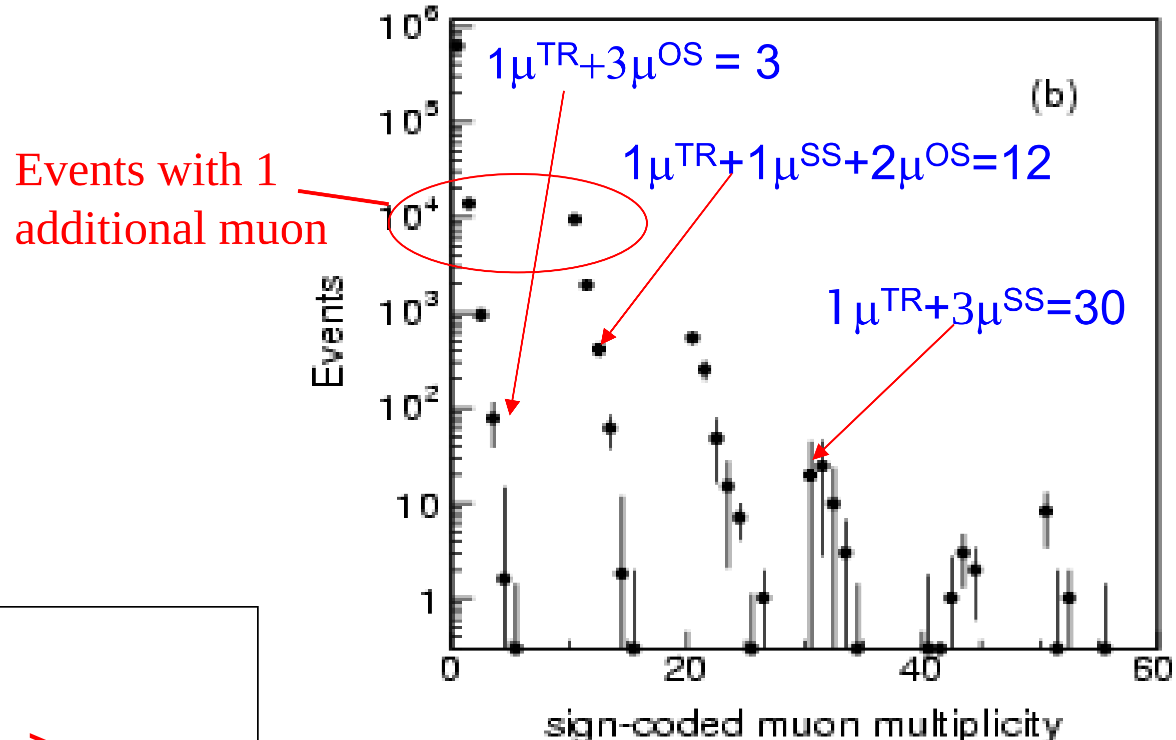
There are 295481 ghost events that contain approximately 28000 real muon combinations with SS or OS charge (9.4%)

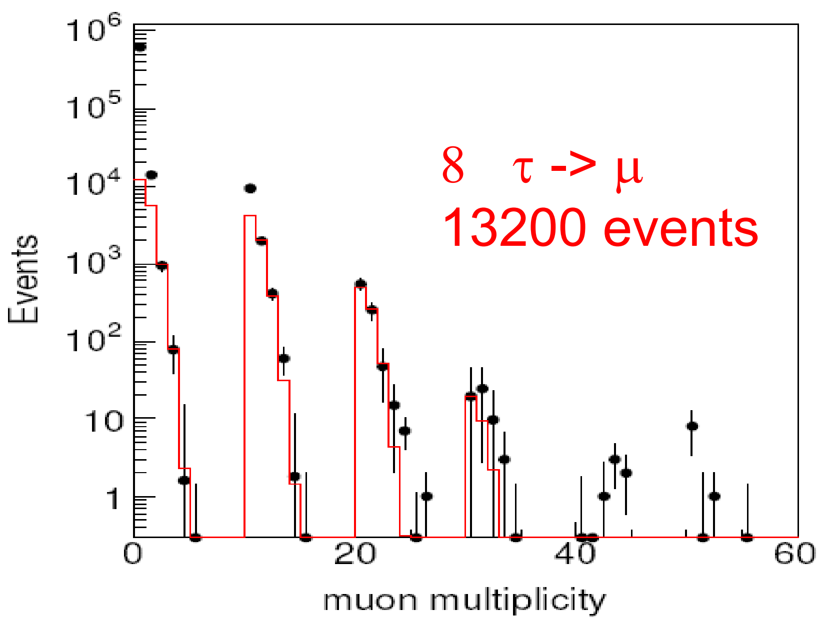
- number of additional muons in ghosts is 4 times larger than in QCD (2.5%)
- Fakes are evaluated using the actual number of tracks; the number of charged tracks (p_T>2GeV) in ghosts is 2 times larger than in QCD

muon multiplicity in a cosθ>0.8 cone

fakes removed

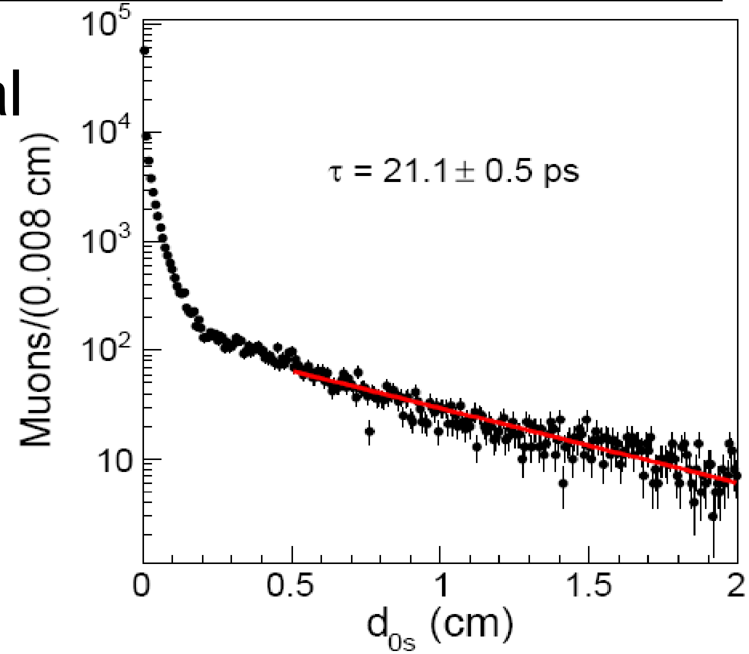
$$\mathcal{M} = N_{OS} + 10N_{SS}$$

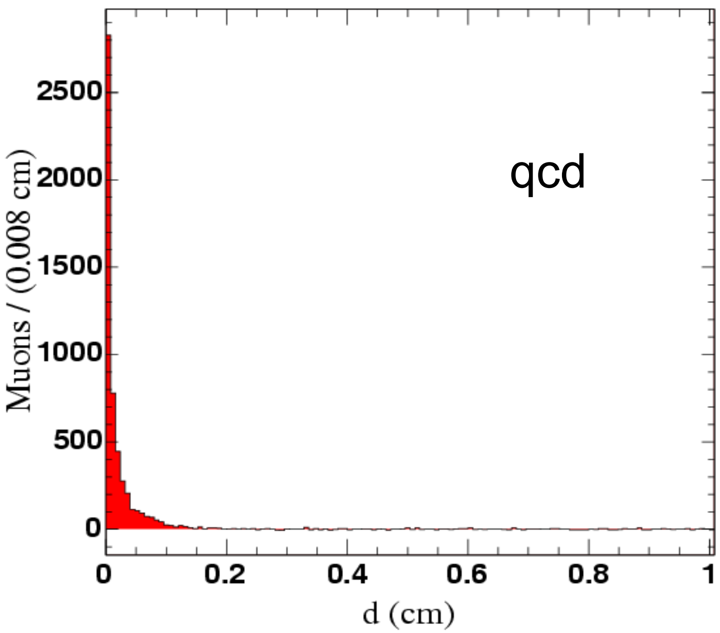


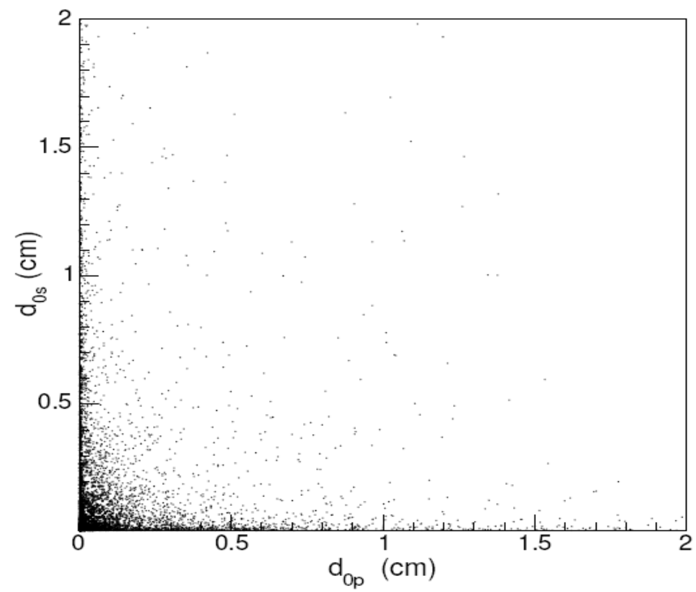


additional muon impact parameter

The impact parameter of the additional muons is consistent with that of initial muons







Conclusions

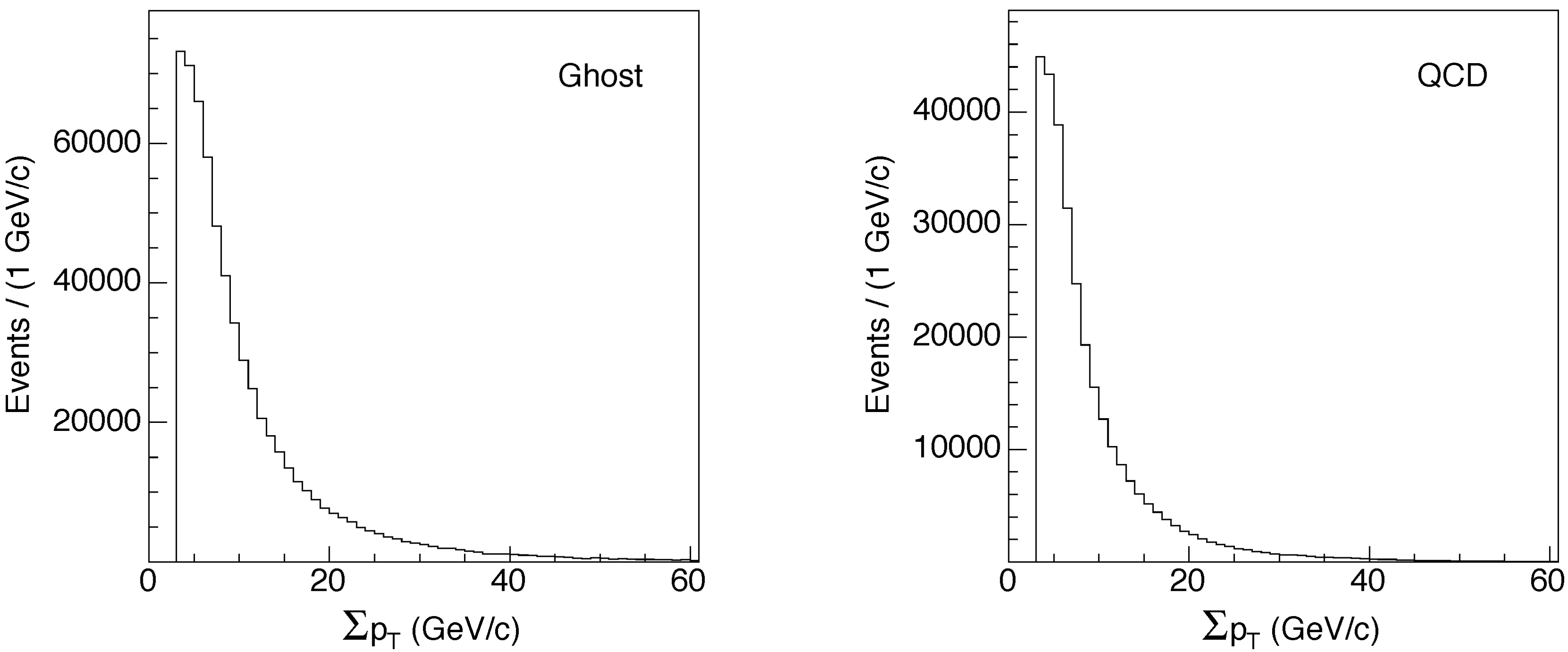
- We have isolated a sample of dimuon events (Ghost) in which one of the muons originates beyond the beam pipe
- The size is comparable to the *bb* contribution
- These events offer a plausible explanation for previous discrepancies with theory (σ_{bb} , $\bar{\chi}$, dilepton invariant mass)
- Most of this ghost contribution is due to IFD
- A small but significant fraction of these events has a muon multiplicity that we cannot explain in terms of known physics
- The impact parameter distribution of the additional muons in these event does not correspond to any known lifetime

spares

Correlated punch through

- Traditionally searches for soft muons performed by CDF estimate the fake muon contribution using a per-track probability. It has been argued that ghost events could be due to a breakdown of this method in presence of events with high E_T jets with many tracks not contained in the calorimeters. We would observed this effect also in the QCD control sample since the energy flow in the jet is similar:

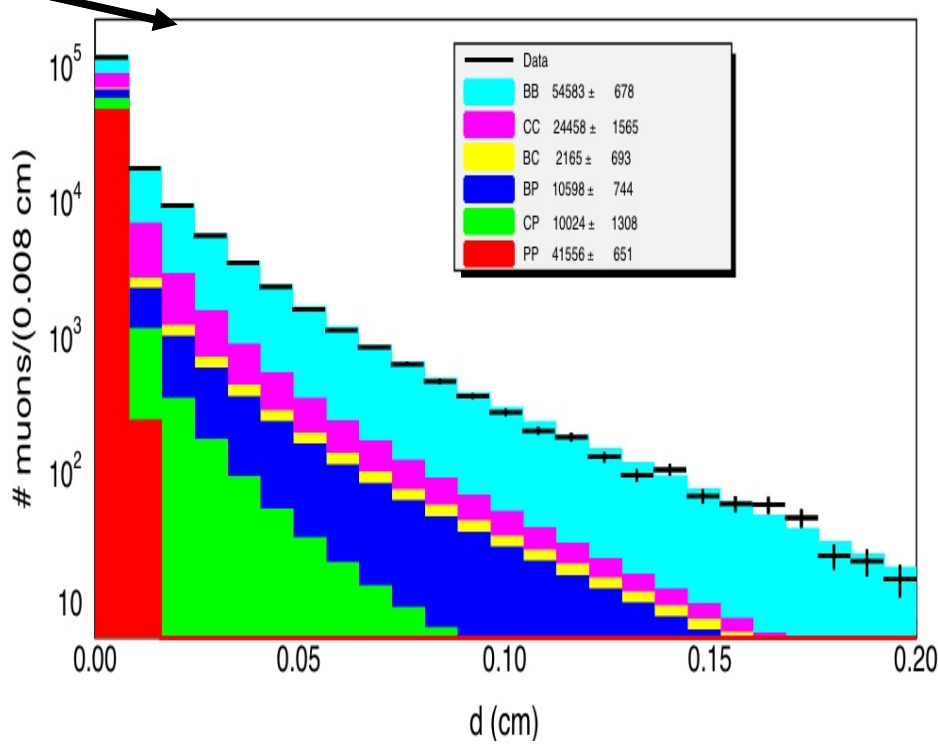
Track p_T sum in cosθ>0.8 cones



Deconstructing the DØ result

The definition of ghost is Ghost = N – N^T/ε, where N is the number of reconstructed dimuon events, N^T is the number of events in which two trigger muons originate inside the beampipe, and ε is the efficiency/acceptance of the silicon detector that validates this latter requirement.

CDF: the sample composition of N^T has been measured. ε has been evaluated using efficiencies derived from the data for prompt and heavy flavor muons, averaged over the known N^T sample composition. N is a measured number, the sample has been studied and is not fully understood in terms of known physics

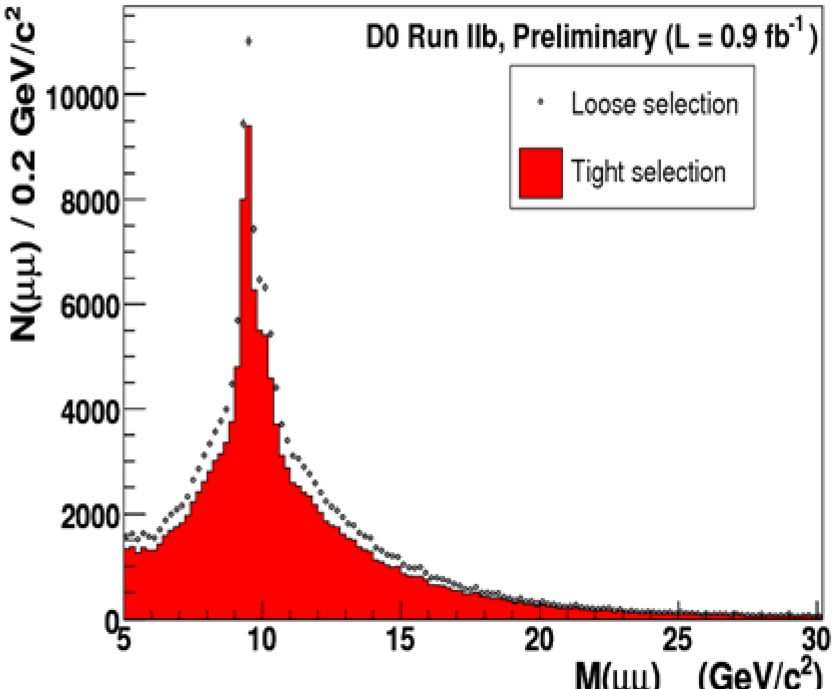


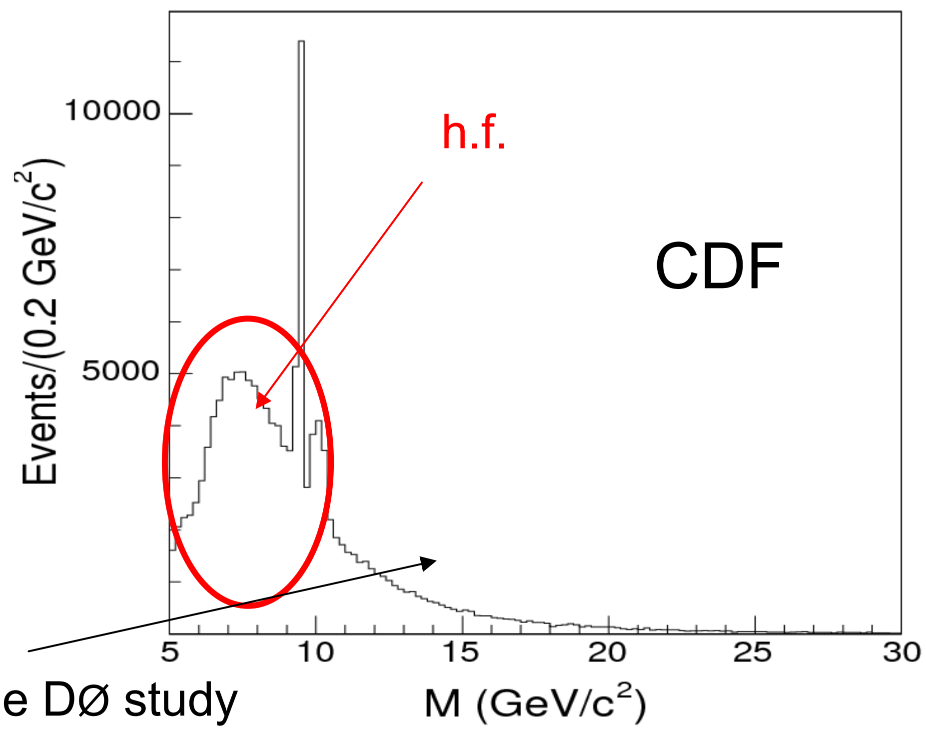
DØ: N and N^T are measured numbers, but the sample composition has not been studied. ε is the efficiency/acceptance for prompt J/psi mesons

A comparison of the two results requires the assumption that samples N or N^T have the same composition in both studies. Will show that this does not seem not the case

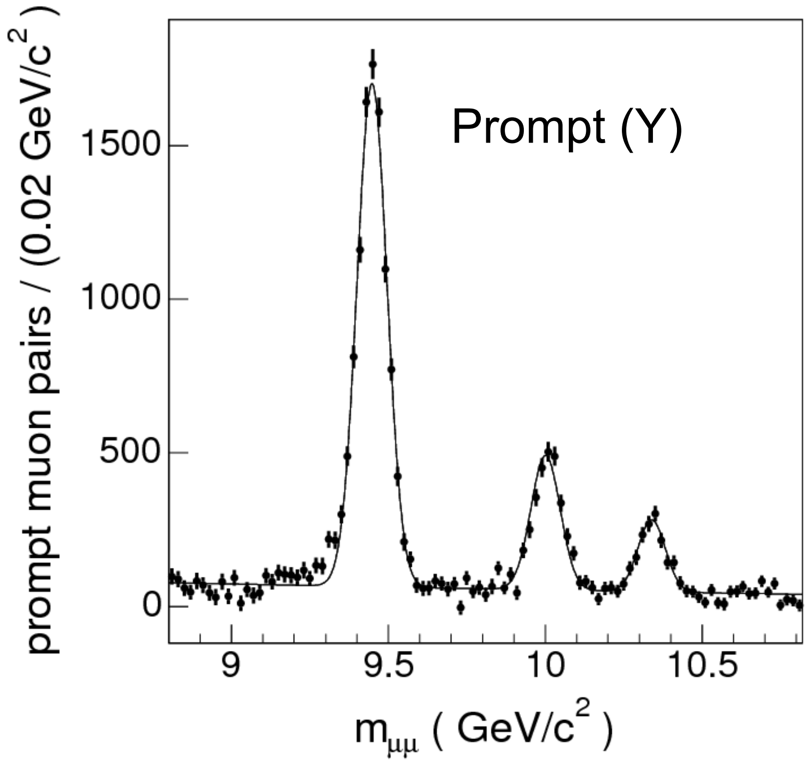
- CDF: selects events with at least two reconstructed muons with p_T >3 GeV/c^2, $|\eta|$<0.6. $\mathcal{L}$ = 742 pb^{-1} and N=743006 events
- DØ: selects events two muons with with p_T >3 GeV/c^2, $|\eta|$<1.0 , $\mathcal{L}$ = 0.9 fb^{-1}. The muon trigger/reconstruction is too convoluted. It is certainly done properly, but difficult to understand. If the sample N reconstructed by DØ were the same as that of CDF, the DØ sample should contain N= 2.5×10^6 events, whereas it contains 2×10^5 events (less than 10%) . What was lost by the trigger and reconstruction ?

Comparison of the dimuon invariant mass in the samples N. Two obvious observations:
- CDF tracks are much better reconstructed
- The sample compositions are different. The heavy flavor contribution seems to have disappeared in the DØ sample. Depending on the mass resolution (not reported) the DØ sample could be dominated by Y mesons



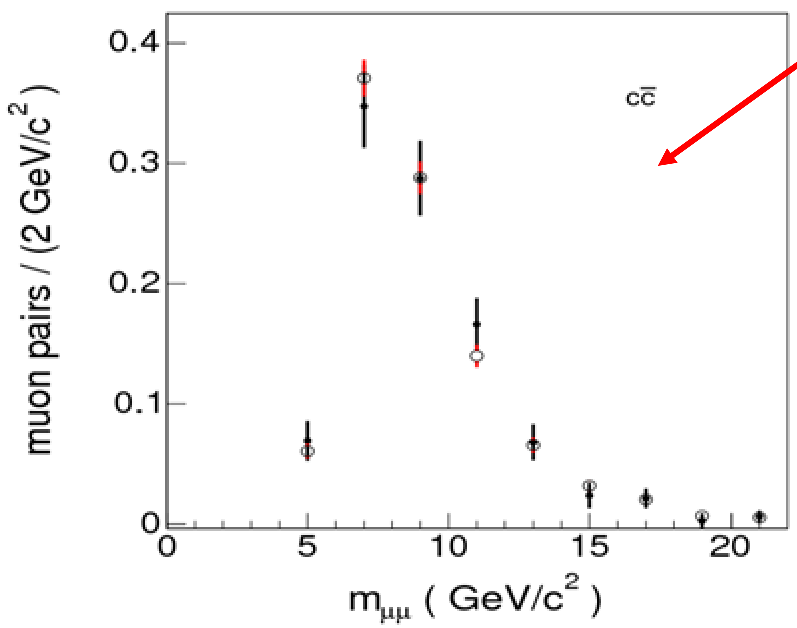


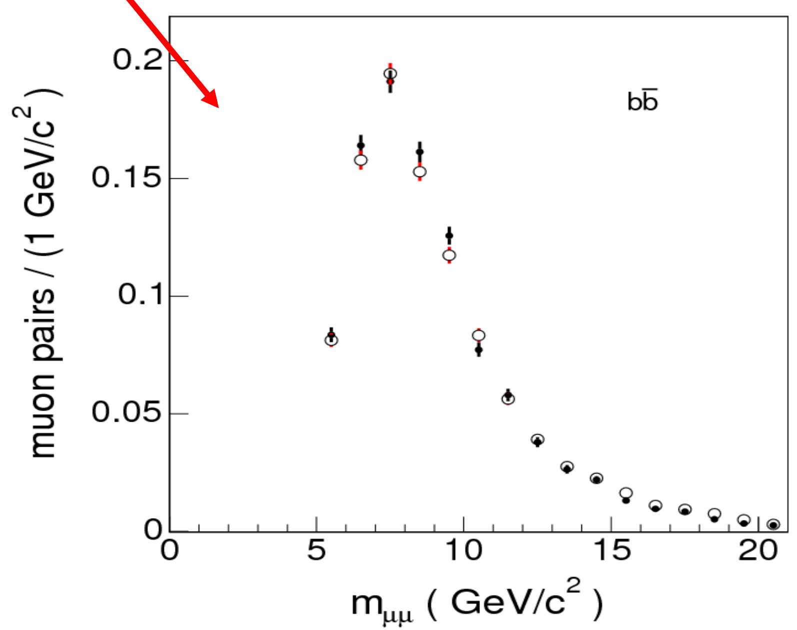
CDF binning chosen to emulate the DØ study



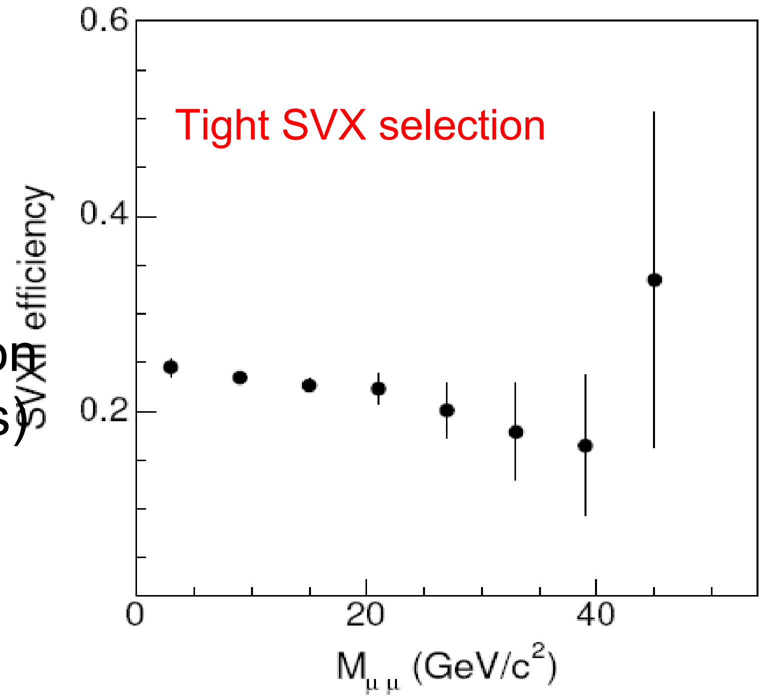
CDF N^T sample. We extract the invariant mass distributions of the different components using the ${}_s\mathcal{P}lot$ statistical method, and compare them to the simulation.

These components are missing in the DØ distribution





DØ measures the efficiency of the N^T selection using prompt J/psi - ε_P=0.844.
We know from data and simulation that the efficiency for heavy flavor is ε_{hf}= 0.92 ε_P
The difference in the efficiencies can be exploited to derive the DØ sample composition in terms of prompts (dominated by Y mesons) and h.f.



N=177535, N^T=149161

DØ calculates SG= N- N^T/ε_P = 712 ± 462 evnts

$$149161 = 177535 \cdot \left[\varepsilon_p \cdot f_p + 0.92 \cdot \varepsilon_p \cdot (1 - f_p)\right]$$

F_P=0.94 F_{hf} = 0.06

Conclusion: the DØ sample is dominated by prompt. Heavy flavors are rejected. The only plausible reason is that the trigger or the track reconstruction efficiency drop at large impact parameter or isolation

CDF:

N=743006 events (SG= multimuons)

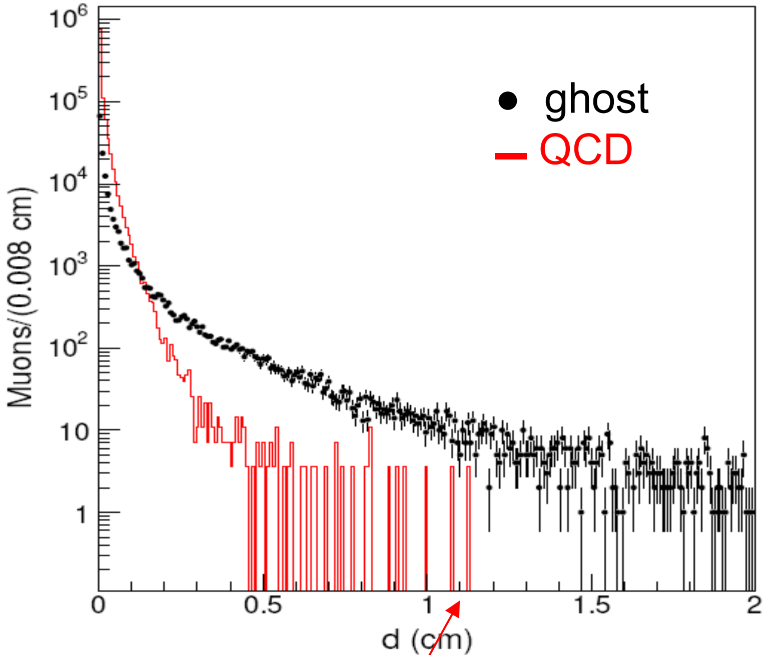
SG	IFD	Ghosts	h.f.	Y's
6600	57000	154000	305500	51700
0.02 h.f.	0.18 h.f.		h.f.=6.14 Y	

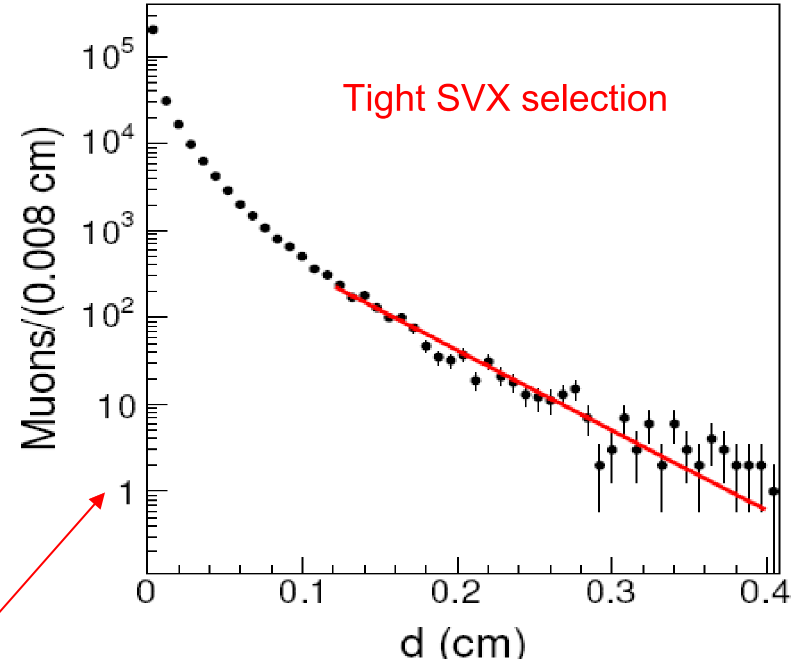
factor 100 reduction

D0:

h.f. = .06 prompt (Y)

DØ needs to evaluate its N sample composition. On the back of an envelope, under the conservative assumption that
`` the 100 reduction factor also holds for the special multimuons (less isolated and with longer lifetime than heavy flavors)"
one derives
SG(D0) = 0.02•0.06•1.7×10^5=200 evts whereas ΔSG(D0)=462 evts



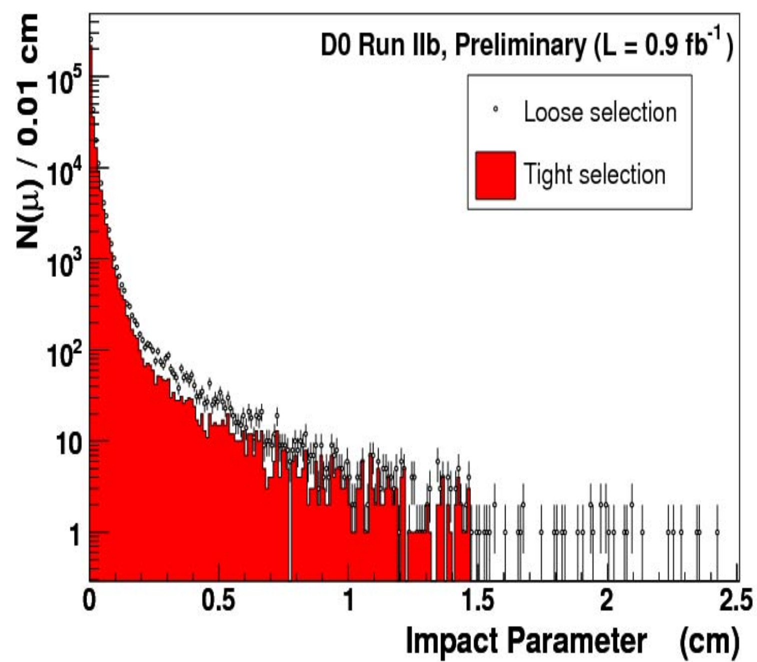


CDF

CDF measures impact parameters with a 30 μm resolution and measures the correct b lifetime.

When muons originate inside the beampipe (1.5 cm), the IP distribution is exhausted at 0.5 cm (b hadron contribution, prompts are exhausted after 60 μm). The IP distributions for N^T and $N-N^T$ are completely different

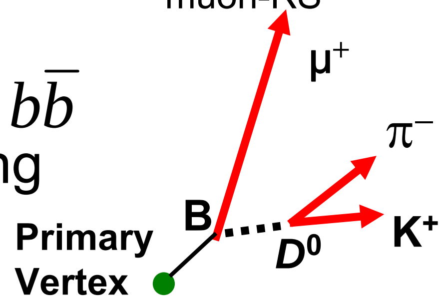
In the case of DO, the IP parameter distribution is almost insensitive to this request. The IP shape reflects their track resolution because 96% of their dimuons are prompt. A poor momentum resolution (Y) is generally accompanied by a poor IP resolution

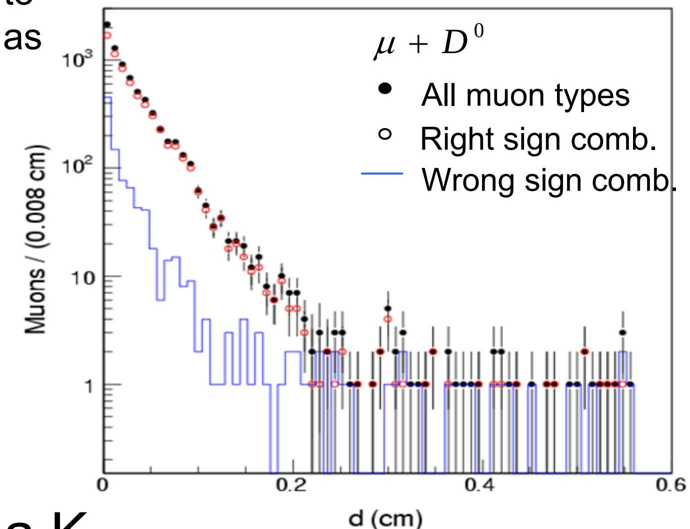


Possible sources of ghost events

- **Track mismeasurements:**
  look at $\mu + D^0$ events.
  Most of them come from $b\bar{b}$
  $d_0(\mu)$ consistent as coming from B's – no long tails

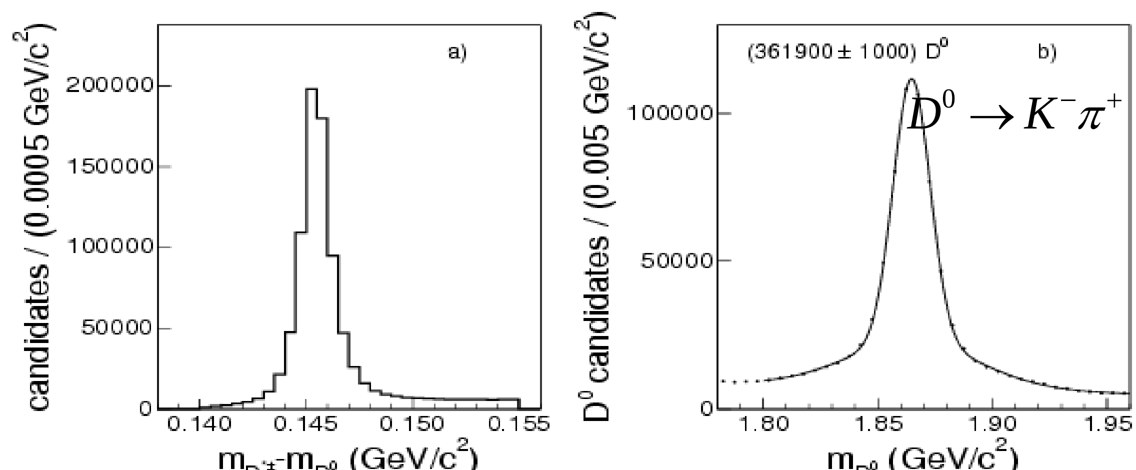
k mass associated to track same charge as muon-RS



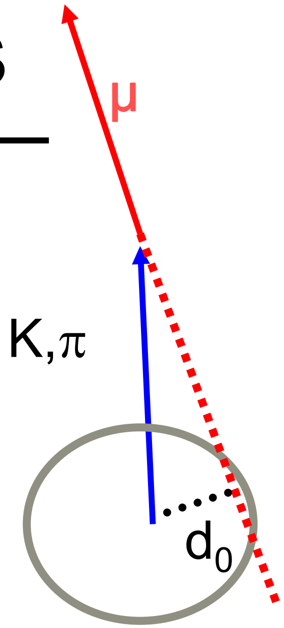


WS: low level of fakes

- **Punch throughs:**
  Measure the probability per track that a π or a K punches through the calorimeter and fakes a muon
  - Reconstruct $D^{*+} \rightarrow D^0\pi^+$ decays with $D^0 \rightarrow K^-\pi^+$
  - D^{*+} uniquely identifies π and K
  - Ask at what rate hadrons are found as muons



Possible sources of ghost events

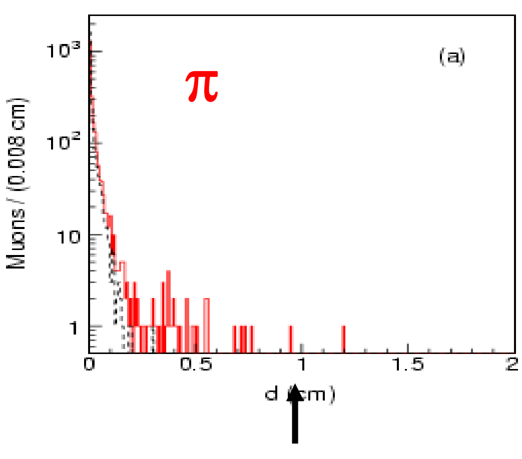


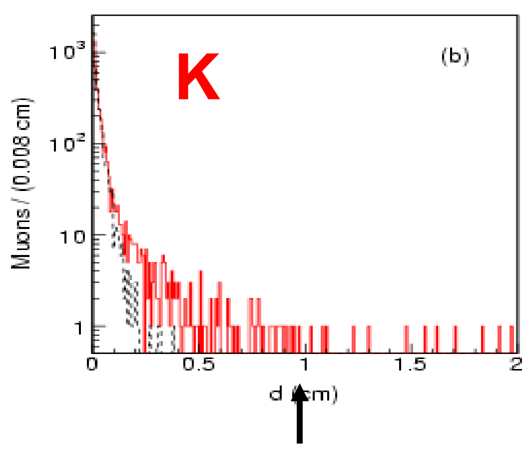
silicon layer

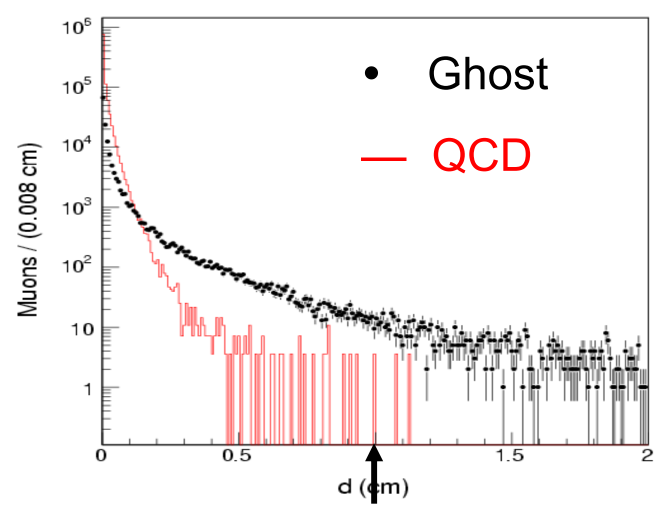
Decays in flight:

- Measure the probability that K and π decays produce CMUP muons (trigger muons) and pass all analysis cuts. Use a heavy flavor simulation [HERWIG].
- Probability per track that a hadron yields a trigger muon is 0.07% for π and 0.34% for K
- Normalize this rate from Herwig MC to measured *bb* cross section
- We predict 57000 events in ghost sample due to decays in flight

In-Flight decays prediction explains 35 % of the ghost events, but only 10% of the events with d_0 > 0.5 *cm.*



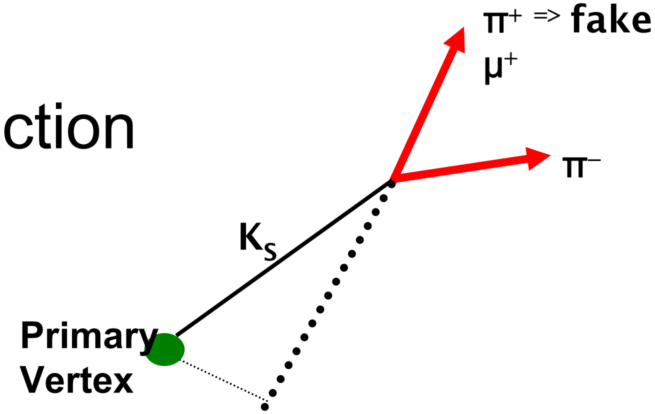




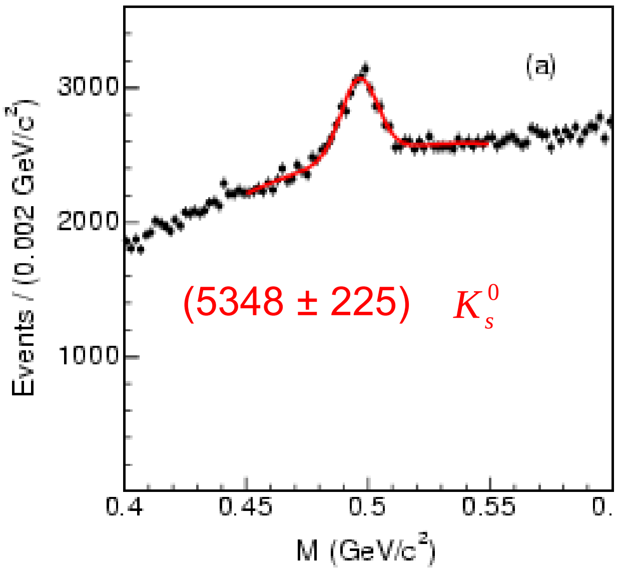
Possible sources of ghost events

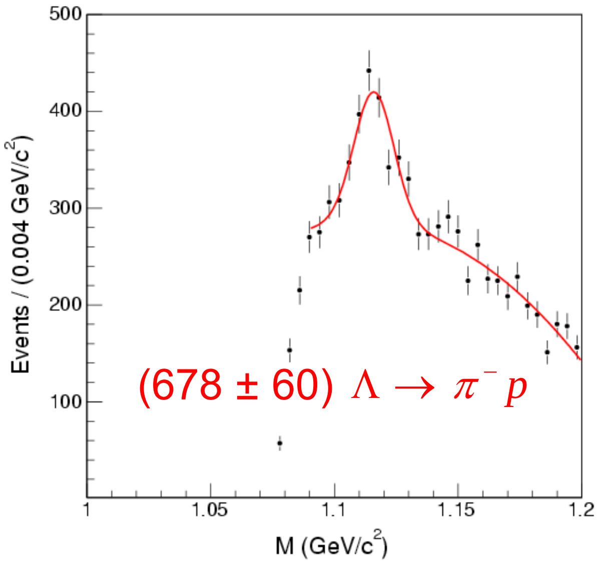
K^0_S and hyperons:

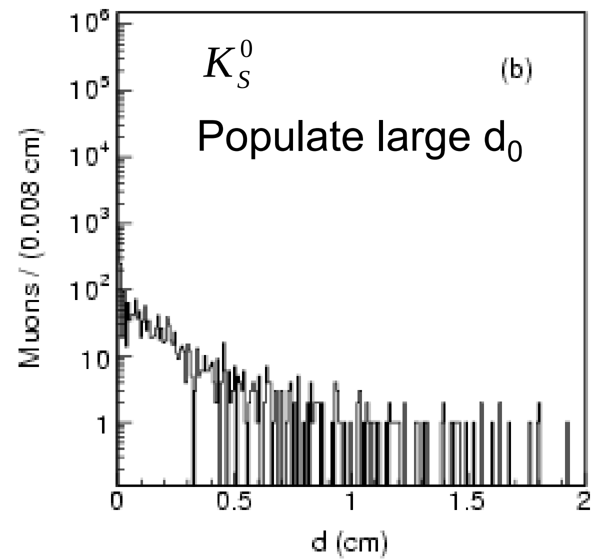
- Kinematic acceptance times reconstruction efficiency ~ 50% (MC).
- Approximately 12000 ghost events are contributed by these decays.



Look for μ+track track p_T > 0.5 GeV/c Assume μ and track are π







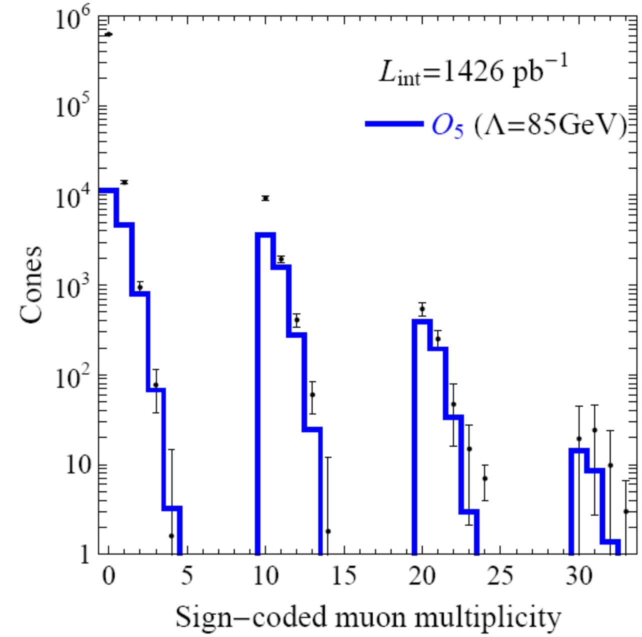
Barbieri et al.

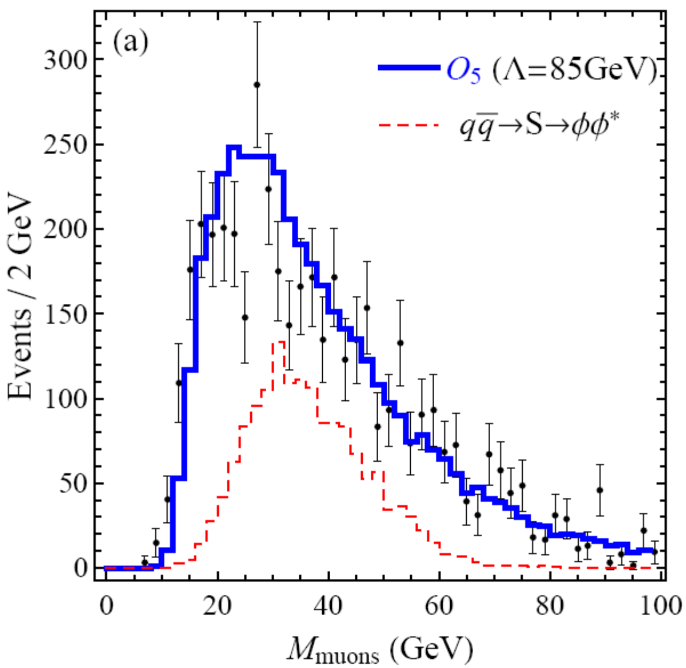
$$O_5 = \frac{1}{\Lambda}(\bar{q}q)|\phi|^2, \qquad p\bar{p} \longrightarrow \phi\phi$$

$$\phi \rightarrow 2\ \phi_1 \rightarrow 4\ \phi_2 \rightarrow 8\ \tau$$

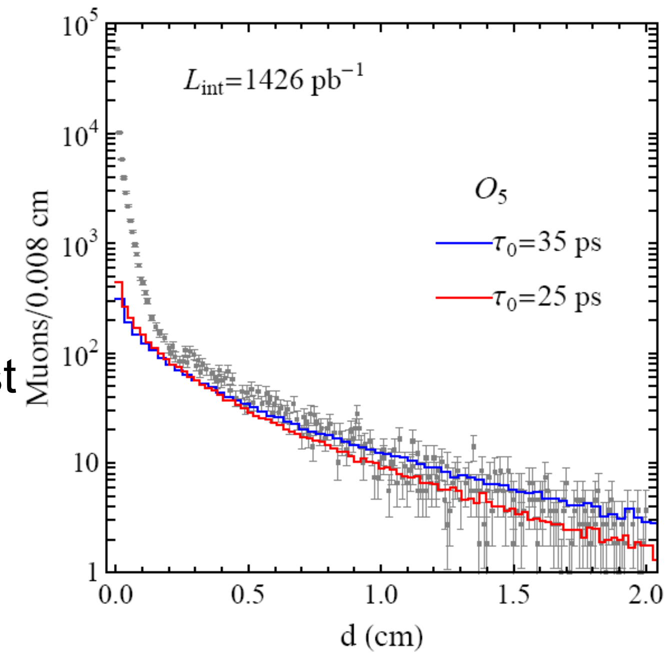
$$m_\phi = 15\,\mathrm{GeV}$$

$\phi_2 \longrightarrow \tau\bar{\tau}$ with a long lifetime



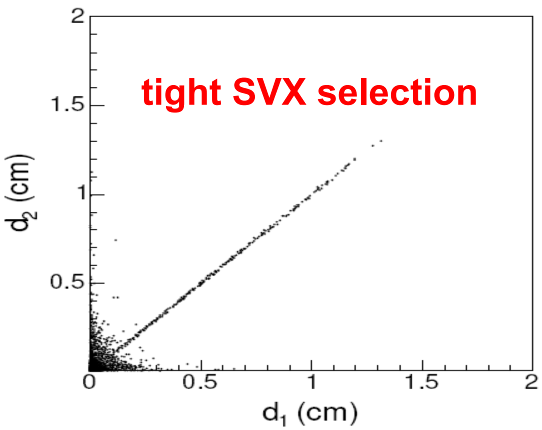


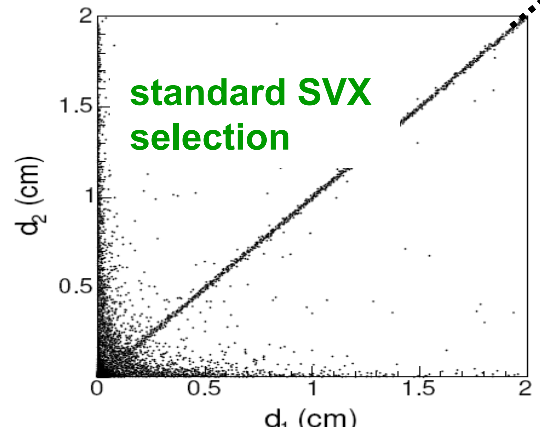
invariant mass of muons in a cone for events with 2 cones with at least 2 muons



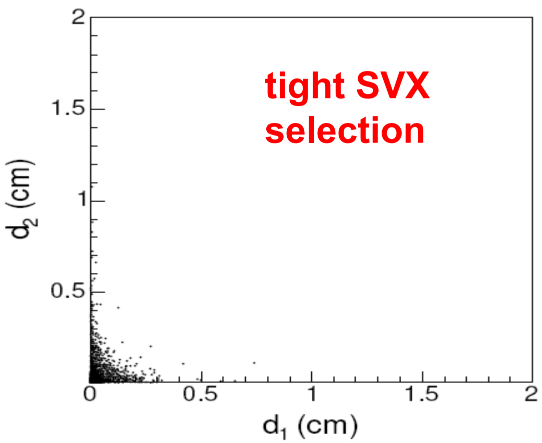
Tracking differences

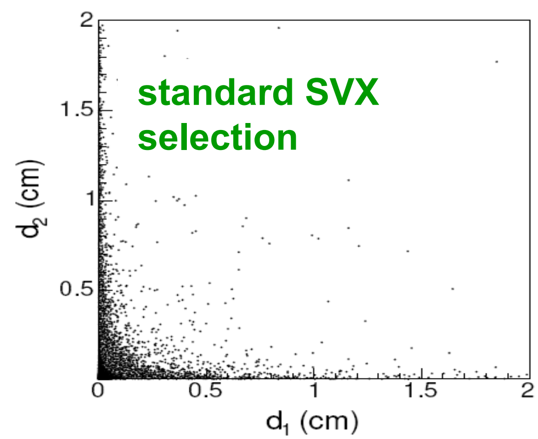
- Analyses in CDF use standard requirements: 3/8(SVX+ISL) layers
  - Muons can originate as far as 10.8 cm from the beam line
  - According to simulation, 96% of QCD events have 2 muons originating inside the beam pipe
- Run I analyses selected muons originating from distances as large as 5.7 cm from the beam line





Cosmic rays overlapping $p\bar{p}$ collisions:
2 back to back muons clustering along the diagonal of $d_0(\mu_1)$ vs $d_0(\mu_2)$





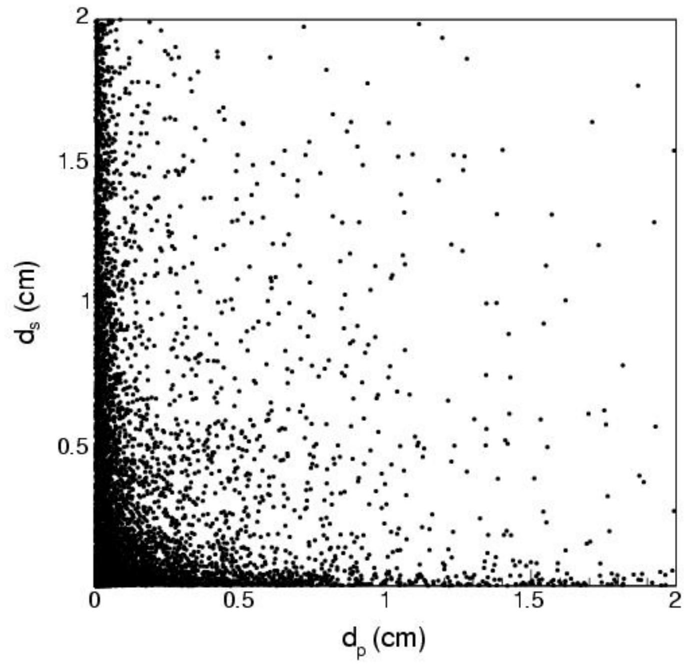
After cosmics removal

$$\vartheta_{\mu^-\mu^+} < 3.135 rad$$

Impact parameter of additional CMUP muons in ghost events

- The salient features of ghost events, like additional track and muon multiplicity higher than that of QCD events, are there when requiring the additional muon to be CMUP (very pure)

- the large impact parameter distribution of additional muons is consistent with the trigger muons



Event display